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Analysis of combining ability over environments in diallel crosses of maize (*Zea mays*)

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Abstract Utilization of stress tolerant maize is the key to sustainable production and food security, and hence studies were conducted at Dirab Research Station, Riyadh, Saudi Arabia, from 2009 to 2010 to estimate General Combining Ability (GCA), Specific Combining Ability (SCA) and their interactions with environment. Non-reciprocal diallel crossing was performed among six inbreds. The inbreds, 15 F_1 hybrids and two checks were evaluated in split plot design. Regulated irrigation commenced before tasselling and stopped before grain filling stage, using Food and Agriculture Organization (FAO) evaporation pan as guide. Water was applied when pan reading was at 50, 70 and 90 in. to create E1, E2 and E3 environments respectively. Data were analyzed using method 3 of Gardner and Eberhart. Analysis of variance showed highly significant variance ($P \leqslant 0.01$) among almost all sources of variation. High significance GCA and SCA observed revealed the importance of both additive and non-additive genetic actions, while low GCA/SCA implied importance of dominant effects of gene. Anthesis-silking interval (ASI) was the most affected trait by water deficit indicating that selection for tolerance could be based on short ASI. Performance per se of the genotypes reveals the importance of hybrids with P1 and P6 but failed to indicate their suitability as combiners. The KSU 6–47 had highest significant GCA for grain yield under E1 and E2. KSU 3–69 had the lowest significant negative GCA for days to tasselling, while cross KSU 6–47 × KSU 3–69 with high SCA for grain yield and 1000-kernel weight under all environments suggested their usefulness for improvement.

1. Introduction

Maize is an important global grain crop grown in Saudi Arabia basically as a component of feed. In a preliminary study, El-Sharif (1986) showed the potential of maize production in the Kingdom and its role in food security. As a result, the annual hectare planted with this crop increased from more

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than 5000 hectare in the seventies to more than 15,000 hectare in the new millennium (CIMMYT, 2015). This increase was directly associated and supported with reclamation of marginal lands, use of improved maize varieties, water irrigation and fertilizers. Despite this effort, demand for animal protein in the Kingdom continues to grow and requests for intensification of maize production. However water, an essential commodity in farming, can hinder the self sufficiency goal simply because it may quick deplete if mismanaged. Additionally, water deficit can occur at any stage of maize growth, but stress on maize at reproductive (mid-growth) stage was reported to cause the highest ever known grain loss (Atteya, 2003 and Ghooshchi et al., 2008). This observation leads Chapman et al. (1997) to state that selection for tolerance to mid-season drought stress would improve broad adaptation, and specific adaptation to drought environments.

Decision on the genotypes that should be employed for improvement of crop yield under water deficit condition is critical to the success of the entire program. The good performance of varieties in a large number of yield trials simply indicates their relative superiority but does not necessarily reflect their ability to transmit the interesting character when crossed with a number of similar varieties. One of the suitable means to detect performance of offsprings is diallel mating system, a method whereby the parents and progeny performance can be statistically separated into components relating to GCA and SCA. Several methods for analysis have been adopted in which parents may be pure lines or open pollinated varieties. The analysis limited to the homozygous parents and F_1 generation allows estimation of genetic parameters unbiased by linkage and assessment of dominance in the polygenic systems under study effects (Mather and Jinks, 1982).

Combining ability analysis is employed to identify the better combiners which can be hybridized to exploit heterosis and to select better crosses for direct use or further breeding work. The 'expected' value of any particular cross, according to Allard (1960), is the sum of the GCA's of its two parental lines, while the deviation from this expected value is called SCA. GCA values therefore describe the general usefulness of the parental form in terms of the concerned trait, whereas SCA indicates importance of the joint action of the genes of parental forms (Baker, 1978). The occurrence of a considerable variability in SCA effects for a given trait in the starting material for breeding is unfavorable because it increases the probability of obtaining hybrid progenies with an average value of that trait. The amount of improvement expected to come from GCA and SCA will be proportional to their variances (Griffing, 1956). The mean square ratio for GCA and SCA is employed to determine the prevailing gene actions (additive or non-additive) of a quantitative trait. The closer the ratio is to unity, the greater the performance of the progeny selected based on GCA values (Baker, 1978).

There is no agreement among authors on the mode of gene action controlling maize yield or its related characters. It was reported by Nigussie and Zelleke (2001), Vacaro et al. (2002), El-Shouny et al. (2003) and Ojo et al. (2007) that additive genetic action was more important for maize traits suggesting for rapid improvement in selection. However Chaudhary et al. (2000) and Abdel-Moneam et al. (2009) showed that dominance gene effect was important in the inheritance of maize characters. In addition, Nass et al. (2000) and Pswarayi and Vivek (2008), obtained significant ($P < 0.05$) GCA × E and SCA × E for almost all traits studied, an indication of variation of general combining ability of lines under different environments. This study was designed to estimate the combining abilities of the inbreds and hybrids under three water regimes and determine effects of environments on expression of both GCA and SCA.

2. Materials and methods

2.1. Description of experiment location and planting operation

The studies were carried out at the Agricultural Research Station at Dirab, (24°46′N and 25°34′E) 40 km southwest of Riyadh, Saudi Arabia. Soil samples were collected from the 0–20 cm, 20–40 cm and 40–60 cm depth and analyzed for chemical and physical characteristics at the Ministry of Agriculture and Water resources laboratory located in Riyadh, Saudi Arabia. The soil is classified as sandy and characterized by pH (H_2O) 7.62, total N: 0.00 g kg^{-1}, available P: 9.33 mg kg^{-1} (Mehlich method), exchangeable K: 186 cmol kg^{-1}. Other related properties of top soil are as follows: water holding capacity is 0.18 v/v% and wilting point is 0.09%. During the experiment period, rainfall was zero, while minimum temperature ranged from 25.87 °C in July to 12.71 °C in November. Maximum temperature also ranged from 43.8 °C in July to 26.08 °C in November.

Six promising inbreds were sown at different dates in July 2009 by planting medium maturing genotypes before early maturing genotypes at fifteen days interval to achieve proper synchronization of flowering between parents. Detail of the inbreds is given in Table 1. Cross pollination was done using all possible combinations without reciprocals to give a total of 15 crosses following the procedure outlined by Russell and Hallauer (1980). The set of fifteen F_1's and their six parents were grown in July 2010. Land preparation was done by harrowing, ploughing and disking the soil at appropriate intervals. The sowing was done by putting two seeds in a hole and later thinned to one plant per hill to maintain a row-to-row and plant to plant distances of 75 and 20 cm respectively. A compound fertilizer in form of NPK 18:18:0 was applied before planting. Weeding was carried out manually 3 times during the growing period.

2.2. Experimental layout

The experiment was in a split-plot arrangement with irrigation rates as main factor and genotypes as subfactor using three replicates in a randomized complete block design (RCBD). Each plot was 1.8 m × 17.25 m and comprised of 23 rows with 5 m pathways between each block to prevent influx of water among the blocks.

The effect of stress on maize yield at the vegetative or grain filling stage is less pronounced than at flowering stage; therefore, stress treatment was limited to reproductive period and stopped before grain filling stage. The planned irrigation commenced a week from tasselling and lasted for 28 days. Water was applied to the plot assigned as optimal environment (E1), intermediate environment (E2) and low environment (E3), when level of water in the pan reduced by 50, 70 and 90 in. respectively. The amount of irrigation water given to each plot was estimated using Etc for maize which was

Table 1 Maize lines used in diallel crossing.

Code	Line name	Sources	Status	Pedigree
P1	CML 161	International Maize and Wheat Improvement Center (CIMMYT), Mexico	Inbred	G25QC18H520-1-1#-1-2#-5-3-B-1-BBBB-#
P2	CML 424	International Maize and Wheat Improvement Center (CIMMYT), Mexico	Inbred	G21C22H169#-1-2-1-1-BBBBBBB
P3	KSU 8–33	Cereal programme of King Saud University, Saudi Arabia	Inbred	Developed from hybrid DAHAB
P4	KSU 4–58	Cereal programme of King Saud University, Saudi Arabia	Inbred	Developed from Pioneer 3065
P5	KSU 6–47	Cereal programme of King Saud University, Saudi Arabia	Inbred	Developed from Giza single cross 152
P6	KSU 3–69	Cereal programme of King Saud University, Saudi Arabia	Inbred	Developed from Giza single cross 161
	NC + 7117	NC + Hybrids Co., Lincoln, NE 68504 USA	F_1 Hybrid	Commercial variety
	Panama	ICS/Maïsadour Semences, France	F_1 Hybrid	Commercial variety

calculated by the FAO Penman Monteith method of Allen et al. (1998). The duration of the induced stress was 28 days and E1, E2 and E3 received water for 8, 6 and 4 times respectively. Each plot was irrigated for ten minutes and the flow rate was 60 l min^{-1} measured by flow meter installed at water entry of each plot.

2.3. Data collection and analysis

Observations were made on eight competitive plants of the two middle rows in each plot. Data were collected on the following characters: leaf rolling (each plant row was visually scored on a scale of 1–5 with 1 indicated turgid-unrolled and 5 V shape rolling), leaf area index (computed by multiplying flag leaf length by width by 0.75 – a constant value Montgomery and Doak (1970)), plant height (Average height of plants in centimeters (cm) measured from soil surface to the point on stem where tassel branching begins), days to anthesis and days to silking (number of days from planting to the date when 50% of the plants in a row have visible silk and tassel shedding pollen respectively), anthesis-silking interval (number of days to 50% anthesis minus number of days to 50% silking), kernel weight (actual weight of 1000 grains at 14% moisture content), and grain yield (grams of grain shelled from harvested ears adjusted to 14% moisture content). Data were analyzed using combined analysis of variance (ANOVA), with irrigation rate (environments), maize genotypes, GCA, SCA and interactions among them being the focus using model 1 fixed effects of both environments and genotypes according to Steel and Torrie (1980). Data were subjected to analysis of variance using Statistical Analysis Software (SAS) Version 9 for windows (SAS, 2000). Significant genotypic variance of each trait was further partitioned to GCA, SCA and experimental error. Daily Temperature in the area was obtained from meteorological station located in the site, from which monthly average minimum and maximum air temperature was calculated. Combining ability analysis was performed according to method 3 of Gardner and Eberhart (1966) using this following mathematic model:

$$X_{ij} = \mu + g_i + g_j + s_{ij} + e_{ij}$$

where:

X_{ij} = Value of the progeny derived from the crossing of ith female parent with jth male parent.
μ = Mean effect for all progenies.
g_i = The GCA effects of the ith female parent.
g_j = The GCA effects of the j-th male parent.
s_{ij} = The SCA effects specific to the hybrid of the i-th female and the j-th male line.
e_{ij} = Experimental error (between ith and jth lines)

The relative importance of general and specific combining ability on progeny performance was estimated as the ratio:

$$\frac{2MS_{GCA}}{(2MS_{GCA} + MS_{SCA})} \quad \text{Baker (1978)}$$

where:
MS_{GCA} = Mean square of GCA.
MS_{SCA} = Mean square of SCA.

All calculations concerning the estimation of GCA and SCA effects in the above model, and those concerning the variance analysis and detailed multiple comparisons were carried out using the DIAL-SAS computer program (Zhang et al., 2005).

3. Results

The result of combined analysis of variance for maize characters studied under the three environments is presented in Table 2. The effects of environment, entry and environment × entry interaction were highly significant for all characters. The interaction effects of environment × parent, environment × parent-cross, environment × crosses, environment × GCA and environment × SCA were also highly significant for all characters studied except leaf rolling and grain yield. Highly significant GCA effect was found in leaf area and plant height but significant for kernel weight. All characters showed less than unity values for GCA/SCA ratio. The highest ratio was observed in leaf area index (0.95), while the lowest GCA/SCA ratio (0.40) was obtained from grain yield.

Mean performance of maize characters over the three environments is shown in Table 3. The result revealed an increase in leaf rolling, days to anthesis, days to silking and anthesis-silking intervals with reduction in soil water. In contrast, as moisture decreased a reduction in leaf area index, plant height, 1000 kernel weight and grain yield was recorded. Table 4 dis-

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Table 2 Combined analysis of variance of maize characters under three environments.

SOV	Df	LR	LAI	PH	DAT	DAS	ASI	KW	GY
Replication	2	0.06^{ns}	977.72^{ns}	85.40^{ns}	0.30^{ns}	0.08^{ns}	0.09^{ns}	425.50^{ns}	0.38^{ns}
Env	2	3.06^{**}	339997.05^{**}	11523.37^{**}	49.77^{**}	89.61^{**}	11.40^{**}	69463.76^{**}	7.14^{**}
Entry	22	0.47^{**}	148601.80^{**}	4500.48^{**}	64.49^{**}	53.01^{**}	3.75^{**}	53047.99^{**}	6.56^{**}
Parent	5	0.31^{ns}	265244.80^{**}	9248.19^{**}	120.03^{**}	99.59^{**}	2.53^{ns}	61556.37^{*}	12.26^{**}
Parent × cross	1	0.01^{ns}	673140.08^{**}	23097.09^{**}	289.74^{ns}	248.27^{*}	1.60^{ns}	204759.50^{**}	44.04^{*}
Cross	14	0.57^{ns}	83015.85^{**}	1925.75^{**}	29.48^{ns}	24.03^{ns}	4.53^{ns}	45413.76^{**}	2.23^{ns}
GCA	5	0.50^{ns}	196649.08^{**}	4219.68^{**}	24.24^{ns}	17.99^{ns}	3.57^{ns}	53978.75^{*}	0.99^{ns}
SCA	9	0.61^{ns}	19886.29^{ns}	651.35^{ns}	32.38^{ns}	27.38^{ns}	5.07^{**}	40655.43^{ns}	2.92^{ns}
GCA/SCA		0.62	0.95	0.93	0.60	0.57	0.59	0.73	0.40
Env × entry	44	0.44^{**}	8084.52^{**}	334.03^{**}	19.76^{**}	17.44^{**}	2.90^{**}	14173.90^{**}	1.33^{**}
Env × parent	10	0.34^{ns}	6795.72	220.50^{**}	10.18^{**}	12.97^{**}	3.49^{*}	16213.19^{**}	1.51^{ns}
Env × Var − cross	2	1.55^{ns}	1384.70^{**}	51.98^{**}	21.51^{**}	11.78^{**}	3.52^{*}	2111.11^{**}	1.88^{ns}
Env × cross	28	0.43^{ns}	9783.55^{**}	432.65^{**}	24.78^{**}	20.48^{**}	2.96^{*}	15421.21^{**}	1.35^{ns}
Env × GCA	10	0.70^{ns}	7663.47^{**}	332.56^{**}	26.79^{**}	27.45^{**}	3.20^{*}	11532.21^{**}	1.36^{ns}
Env × SCA	18	0.27^{ns}	10961.38^{**}	488.26^{**}	23.66^{**}	16.61^{**}	2.83^{*}	17581.76^{**}	1.34^{ns}
Error	136	0.17	2043.38	95.91	1.29	1.32	0.12	1977.00	0.24

ns: Non-significant at 0.05%, Env: environment, LR: leaf rolling, LAI: leaf area index, PH: plant height, DAT: days to anthesis, DAS: days to silking, ASI: anthesis-silking interval, KW: 1000-kernel weight and GY: grain yield.
* Significant at 0.05% probability level.
** Significant at 0.01% probability level.

Table 3 Mean performance of maize characters and yield under three environments.

Characters	E1	E2	E3	$LSD_{0.05}$
Leaf rolling	1.87	2.10	2.29	0.14
Leaf area index	709.76	576.38	544.14	15.22
Plant height (cm)	103.50	85.11	78.58	3.30
Days to 50% anthesis	52.28	53.75	53.75	0.38
Days to 50% silking	53.68	55.25	55.90	0.39
Anthesis-silking interval	1.40	1.49	2.15	0.12
1000-kernel weight (gm)	578.80	556.36	516.17	14.97
Grain yield (t ha^{-1})	3.98	3.93	3.40	0.16

E1 = optimal irrigation, E2 = intermediate irrigation and E3 = low irrigation.

plays the performance of maize genotypes for all characters over the three environments. In general, F_1 hybrids outperformed the inbreds except in few instances. P2 and P3 were the best maize lines for plant height (208 cm) and anthesis-silking interval (0.67 day) under E3, while P2 (48.5 days) and P1 (0.5 day) respectively displayed the best performance for days to silking and anthesis-silking interval under E1. The result further showed that the diallel crosses were better than the two commercial hybrids tested, though NC + 7117 was the best for plant height with 239 cm under E1. It was also noted that the hybrids with P1 or P6 parental background were the best for displaying high values in almost all the characters in all environments.

Data on general combining ability (GCA) effects of maize parent characters under three environments are presented in Table 5. P1 had highly significant positive GCA effect of leaf area index in all three environments: E1, E2 and E3 (74.27, 79.63 and 98.40 respectively) and highly significant GCA of 1000-kernel weight under E2 and E3 with values of 77.77 and 48.63 respectively. Highly significant positive GCA of plant height was found in P1 under E2 and E3 with 14.15 and 7.76 respectively, in addition to highly significant positive GCA of leaf rolling under E3 (0.55). In the same vein, significant negative GCA of anthesis-silking interval was recorded for P1 under E2 (−0.25).

Highly significant positive GCA of leaf area index was recorded for P2 under all environments with values of 100.48, 90.63 and 106.54 respectively, whereas highly significant GCA of plant height occurred under E2 and E3 (13.62 and 15.41 respectively). Similarly, P2 showed highly significant positive GCA of 1000-kernel weight under E2 and E3 with values of 75.58 and 50.22 respectively and significant positive GCA under E1 (23.62). P2 also depicted highly significant positive GCA of grain yield under E3 (0.44) and highly significant negative GCA of anthesis-silking interval under E2 (−1.08). Similarly, P4 had highly significant negative GCA of anthesis-silking interval under E1 and E3 (−0.79 and −0.67 respectively). It also showed highly significant negative GCA of leaf rolling (−0.36) and days to anthesis were under E3 only (−2.90). P4 also displayed highly significant negative GCA (−3.57), but highly significant positive GCA (5.67) under E3.

Also, P5 had highly significant negative GCA of leaf rolling (−0.28) under E3 environment in addition to highly significant negative GCA of days to anthesis (−0.86) and highly significant negative GCA of days to silking (−0.90) under E2. Further, P5 depicted highly significant positive GCA of grain yield under E1 and E2 (0.35 and 0.53 respectively). In respect of P6, highly significant negative GCA of days to anthesis was found under the three environments with values of −1.15, −1.99 and −0.74 respectively. The cross also had highly significant negative GCA of anthesis-silking interval under E1 (−0.21). Additionally, P6 showed positive significant GCA under E3 (1.96) and highly significant negative GCA of days to silking under E2 (−1.24).

Specific combining effects of seven characters of fifteen F_1 maize hybrids under three environments are given in Table 6. P1 × P2 had highly significant negative SCA of days to anthesis and days to silking under E1 and E3. It further showed

Table 4 Mean performance of grain yield of maize genotypes under three environments.

Genotypes/environments	LR			LAI			PH (cm)			DAT		
	E1	E2	E3	E1	E2	E3	E1	E2	E3	E1	E2	E3
P1	1.33	2.33	2.00	743	626	659	213	193	196	51.5	52.3	54.0
P2	1.00	2.00	2.67	767	705	674	233	209	208	48.5	51.0	50.8
P3	2.00	2.33	2.33	315	245	224	188	149	115	57.2	64.7	59.5
P4	2.00	2.67	2.33	576	385	296	160	151	142	55.5	57.0	57.7
P5	2.00	2.67	2.00	645	445	418	192	161	138	51.0	56.7	54.3
P6	2.00	2.33	2.00	464	417	377	145	125	136	57.5	58.7	54.5
P1 × P2	1.67	2.00	2.33	789	698	705	216	210	191	48.5	53.2	55.5
P1 × P3	2.00	2.33	3.67	719	597	689	237	194	151	50.5	55.5	59.7
P1 × P4	2.33	2.00	2.33	766	714	696	225	176	167	54.5	54.0	47.8
P1 × P5	1.67	2.00	2.33	725	719	579	228	236	179	52.7	52.7	56.7
P1 × P6	1.67	2.33	3.33	826	645	608	215	213	162	51.0	48.7	58.7
P2 × P3	1.67	2.33	2.00	707	725	665	212	210	205	49.0	52.5	49.7
P2 × P4	2.33	2.00	2.00	743	715	769	160	228	203	57.2	53.5	50.0
P2 × P5	2.00	2.33	2.33	813	684	591	200	213	162	52.0	51.8	56.7
P2 × P6	2.00	2.00	3.00	877	595	580	197	166	177	51.0	56.0	56.2
P3 × P4	2.00	2.00	2.00	584	480	431	225	206	200	52.2	53.3	54.5
P3 × P5	2.00	2.33	2.00	617	465	382	203	201	189	51.3	55.5	52.3
P3 × P6	2.00	1.00	2.00	455	513	445	189	189	182	51.2	48.0	48.7
P4 × P5	2.00	1.67	2.00	670	553	467	207	176	165	51.7	50.8	52.0
P4 × P6	2.00	1.67	2.00	602	499	491	200	173	170	50.3	53.7	50.0
P5 × P6	2.00	1.67	2.00	690	561	551	196	187	158	49.3	48.2	49.5
NC + 7117	1.33	2.00	2.00	779	644	672	239	211	197	53.3	51.0	51.3
Panama	2.00	2.33	2.00	734	629	546	201	178	180	55.7	57.7	56.3
$LSD_{0.05}$	0.56	0.77	0.6	86.6	67.5	67.7	14.9	21.9	24.2	2.37	1.66	1.41

Genotypes/environments	DAS			ASI			KW (g)			GY (t ha^{-1})		
	E1	E2	E3	E1	E2	E3	E1	E2	E3	E1	E2	E3
P1	52.0	54.5	57.7	0.50	2.17	3.67	690	596	471.9	4.60	4.53	3.93
P2	50.7	51.7	52.5	2.17	0.67	1.67	642	550	528.7	4.93	4.20	3.70
P3	57.7	65.5	60.2	0.5	0.83	0.67	461	331	330.5	2.90	1.00	0.73
P4	57.7	57.8	58.8	2.17	0.83	1.17	595	521	464.7	3.33	2.73	2.70
P5	51.8	57.7	58.7	0.83	1.00	4.33	564	470	434.9	3.77	2.63	1.47
P6	58.3	59.7	57.8	0.83	1.00	3.33	509	449	333.9	2.10	2.03	1.73
P1 × P2	50.7	54.0	57.0	2.17	0.83	1.50	742	730	601.0	4.70	4.60	4.43
P1 × P3	53.7	57.7	60.5	3.17	2.17	0.83	600	594	588.6	4.57	3.67	2.90
P1 × P4	55.0	55.8	51.0	0.50	1.83	3.17	693	630	581.6	4.37	4.00	3.60
P1 × P5	53.2	54.7	60.0	0.50	2.00	3.33	623	541	507.3	5.17	4.27	2.27
P1 × P6	52.3	50.0	59.3	1.33	1.33	0.67	646	613	367.7	4.60	3.07	2.60
P2 × P3	51.0	53.7	52.0	2.00	1.17	2.33	772	628	539.0	5.23	4.17	3.67
P2 × P4	57.8	54.3	51.0	0.67	0.83	1.00	629	499	436.8	4.40	3.60	3.50
P2 × P5	56.0	52.5	60.3	4.00	0.67	3.67	673	568	549.4	4.97	3.93	3.43
P2 × P6	52.0	56.8	58.00	1.00	0.83	1.83	653	609	511.4	4.70	3.43	2.97
P3 × P4	52.8	55.5	55.3	0.67	2.17	0.83	633	537	464.5	3.93	3.80	3.63
P3 × P5	52.7	56.3	54.7	1.33	0.83	2.33	476	422	367.2	4.37	4.00	2.43
P3 × P6	53.2	52.3	53.0	2.00	4.33	4.33	536	533	500.3	4.47	4.40	3.70
P4 × P5	52.5	52.7	52.7	0.83	1.83	0.67	550	464	400.9	4.00	3.53	3.40
P4 × P6	52.0	55.7	52.2	1.67	2.00	2.17	578	556	540.2	4.30	3.97	3.60
P5 × P6	50.0	51.3	52.3	0.67	3.17	2.83	672	644	631.6	6.03	5.40	4.90
NC + 7117	54.7	52	53.5	1.33	1.00	2.17	597	535	492.3	4.57	4.50	4.37
Panama	57.0	58.5	57.2	1.33	0.83	0.83	615	596	572.1	5.00	4.23	3.67
$LSD_{0.05}$	2.28	1.67	1.51	0.48	0.55	0.65	83.2	74	60.98	0.84	0.77	0.75

ns = non-significant, E1 = optimal irrigation, E2 = intermediate irrigation and E3 = low irrigation. LR: leaf rolling, LAI: leaf area index, PH: plant height and DAT: days to anthesis, DAS: days to silking, ASI: anthesis-silking interval, KW: 1000-kernel weight and GY: grain yield. P1: CML 161, P2: CML 424, P3: KSU 8–33, P4: KSU 4–58, P5: KSU 6–47, P6: 3–69.

* Significant at 5% level of probability.

** Significant at 1% level of probability.

highly significant negative SCA of anthesis-silking interval (−1.1) and highly significant negative SCA of leaf roll under E3 (−0.55) alone. The cross displayed significant positive SCA of 1000-kernel weight (38.03 and 45.81 respectively), with significant positive SCA of grain yield under E1 (0.49) and E3 (0.95). Similarly, the cross P1 × P3 had highly significant

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Table 5 General combining ability effects of maize characters under three environments.

Characters	Environments	P1	P2	P3	P4	P5	P6
LR	E1	−0.11^{ns}	−0.03^{ns}	0.22*	−0.03^{ns}	−0.03^{ns}	0.28^{ns}
	E2	0.19^{ns}	0.19^{ns}	0.03^{ns}	−0.14^{ns}	0.03^{ns}	−0.56^{ns}
	E3	0.55**	−0.03^{ns}	−0.03^{ns}	−0.36**	−0.28**	−0.14^{ns}
LAI	E1	74.27**	100.48**	−111.43**	−40.95**	−3.08^{ns}	−19.30^{ns}
	E2	79.63**	90.63**	−68.66**	−23.37*	−17.88^{ns}	−60.35**
	E3	98.40**	106.54**	−67.57**	−7.32^{ns}	−78.34**	−51.75**
PH	E1	11.90^{ns}	8.32^{ns}	−16.09*	−0.24^{ns}	1.59^{ns}	−5.46^{ns}
	E2	14.15**	13.62**	−13.83**	−7.21**	−0.65^{ns}	−6.08**
	E3	7.76**	15.41**	−10.46**	5.67**	−13.11**	−5.26*
DAT	E1	−0.07^{ns}	0.06^{ns}	−0.82*	2.30**	−0.11^{ns}	−1.15**
	E2	0.39^{ns}	1.14**	0.60*	0.72**	−0.86**	−1.99**
	E3	3.10**	0.51*	−0.28^{ns}	−2.90**	0.31^{ns}	−0.74**
DAS	E1	−0.03^{ns}	0.64^{ns}	−0.40^{ns}	1.31**	−0.15^{ns}	−1.36^{ns}
	E2	0.26^{ns}	0.06^{ns}	1.20**	0.72**	−0.90**	−1.24**
	E3	2.85**	0.47^{ns}	−0.24^{ns}	−3.57**	0.89**	−0.40^{ns}
ASI	E1	0.04^{ns}	0.58**	0.42**	−0.79**	0.04^{ns}	−0.21**
	E2	−0.13^{ns}	−1.08**	0.50**	−0.00^{ns}	−0.04^{ns}	0.75**
	E3	−0.25*	−0.04^{ns}	0.04^{ns}	−0.67**	0.58**	0.33**
KW	E1	2.39^{ns}	23.62*	−2.86^{ns}	−19.32^{ns}	−13.95^{ns}	10.12^{ns}
	E2	77.77**	75.58**	−63.83**	−59.48**	−26.79^{ns}	−3.25^{ns}
	E3	48.63**	50.22**	−21.68^{ns}	−9.13^{ns}	−72.78**	4.74^{ns}
GY	E1	−0.09^{ns}	−0.09^{ns}	−0.09^{ns}	−0.12^{ns}	0.35**	0.03^{ns}
	E2	0.14^{ns}	0.02^{ns}	−0.41**	−0.51**	0.53**	0.23^{ns}
	E3	−0.41**	0.44**	0.18^{ns}	−0.02^{ns}	−0.41**	0.22^{ns}

ns = non-significant, E1 = optimal irrigation, E2 = intermediate irrigation and E3 = low irrigation. LR: leaf rolling, LAI: leaf area index, PH: plant height, DAT: days to anthesis, DAS: days to silking, ASI: anthesis-silking interval, KW: 1000-kernel weight and GY: grain yield. P1: CML 161, P2: CML 424, P3: KSU 8–33, P4: KSU 4–58, P5: KSU 6–47, P6: 3–69.
* Significant at 5% probability level.
** Significant at 1% probability level.

positive SCA of leaf area index under E1 and E3 with (50.95) and (0.78) respectively. Further, P1 × P3 displayed highly significant positive SCA of 1000-kernel weight (52.2) and grain yield (0.62).

In the same vein, significant positive SCA of leaf area index (46.74) was recorded under E2 for P1 × P4, while highly significant positive SCA of plant height occurred under E3 (11.1). P1 × P4 also displayed highly significant positive SCA of 1000-kernel weight under E1 and E3 with values of 111 and 55.9 respectively. Similarly, the cross displayed highly significant positive SCA of grain yield (0.46) under E1 environment, while it displayed highly significant negative SCA of days to anthesis (−5.6) and days to silking (−3.6) under E3. However, the cross P1 × P5 recorded only highly significant negative SCA of anthesis-silking interval (−1.00) under E1. Cross P1 × P6 showed significant positive SCA of plant height (11.99), under E2, and highly significant positive SCA of leaf area index (65.73) under E1 environment. The cross further displayed highly significant negative SCA of days to silking and days to anthesis under E2 (−3.25 and −2.23 respectively), in addition to highly significant negative SCA of anthesis-silking interval under E2 and E3 (−1.03 and −1.52 respectively).

Furthermore, P2 × P3 had highly significant positive SCA of leaf area index under E2 (92.1), but highly significant positive SCA of plant height under E2 and E3 with values of 20.2 and 15.8 respectively. Highly significant negative SCA of days to anthesis and days to silking was recorded for P2 × P3 under the three environments as well as highly significant negative SCA of anthesis-silking interval und only under E1 (−0.5). Significant negative of SCA of days to anthesis (−0.80) was observed for P2 × P3 under E3 with highly significant negative SCA of days to silking under E3 (−1.19). The cross P2 × P4 recorded highly significant positive SCA of plant height (19.03) under E3, with highly significant positive SCA of grain yield under E2 (0.57). However, it showed highly significant negative SCA of anthesis-silking interval under E1 and E3 environments.

P2 × P5 had significant negative SCA of days to anthesis (−0.93) and significant positive SCA of 1000-kernel weight under E2 (50.52). For P2 × P6 highly significant negative SCA of anthesis-silking interval was obtained across all the environments, while highly significant positive SCA of leaf area index was depicted under E1 and E3 (90.6 and 0.53 respectively). Similarly, P2 × P6 had under E1 highly significant positive SCA of plant height and 1000-kernel weight (26.3) and (82.20) respectively. Highly significant positive SCA of 1000-kernel weight and grain yield was depicted by P2 × P6 under E1 with values of (82.2 and 0.64 respectively). Similarly, P3 × P4 under E2 had highly significant negative SCA of anthesis-silking interval under E1 and E3 with values of −0.5 and −0.39 respectively. In the same vein, P3 × P5

Table 6 Specific combining ability (SCA) effects of 6 maize hybrid characters under three environments.

Characters	Environment	P1 × P2	P1 × P3	P1 × P4	P1 × P5	P1 × P6	P2 × P3	P2 × P4	P2 × P5	P2 × P6	P3 × P4	P3 × P5	P3 × P6	P4 × P5	P4 × P6	P5 × P6
LR	E1	-0.15^{ns}	0.18^{ns}	0.27^{ns}	-0.15^{ns}	-0.15^{ns}	-0.20^{ns}	0.18^{ns}	0.10^{ns}	0.10^{ns}	-0.20^{ns}	0.10^{ns}	0.10^{ns}	0.15^{ns}	-0.20^{ns}	0.10^{ns}
	E2	-0.37^{ns}	0.13^{ns}	-0.00^{ns}	-0.20^{ns}	0.47^{*}	0.13^{ns}	-0.03^{ns}	0.13^{ns}	0.13^{ns}	0.13^{ns}	0.30^{ns}	-0.70^{**}	0.20^{ns}	0.13^{ns}	-0.00^{ns}
	E3	-0.55^{**}	0.78^{**}	-0.2^{ns}	-0.30^{ns}	0.28^{ns}	-0.30^{ns}	0.03^{ns}	0.28^{ns}	0.53^{**}	0.03^{ns}	-0.05^{ns}	-0.50^{**}	-0.30^{ns}	-0.10^{ns}	-0.20^{ns}
LAI	E1	-91.4^{**}	50.95^{*}	26.6^{ns}	-51.90^{*}	65.73^{**}	12.4^{ns}	-22.01^{ns}	10.40^{ns}	90.60^{**}	30.50^{ns}	26.03^{ns}	-130.00^{**}	-8.40^{ns}	-44.00^{ns}	7.07^{ns}
	E2	-83.00^{**}	-25.00^{ns}	46.74^{*}	46.65^{*}	14.82^{ns}	92.10^{**}	36.97^{ns}	0.55^{ns}	-46.60^{*}	-38.80^{*}	-59.30^{**}	31.30^{ns}	16.70^{ns}	-28.00^{ns}	28.80^{ns}
	E3	-0.55^{**}	0.78^{**}	-0.30^{ns}	-0.30^{ns}	0.28^{ns}	-0.30^{ns}	0.03^{ns}	0.28^{ns}	0.53^{**}	0.03^{ns}	-0.05^{ns}	-0.50^{**}	-0.30^{ns}	-0.10^{ns}	-0.20^{ns}
PH	E1	-16.00^{ns}	6.58^{ns}	18.10^{ns}	-2.95^{ns}	-5.99^{ns}	13.20^{ns}	-15.93^{ns}	-7.90^{ns}	26.30^{**}	-1.10^{ns}	1.09^{ns}	-19.70^{*}	-4.70^{ns}	-5.70^{ns}	5.06^{ns}
	E2	-14.90^{**}	-6.10^{ns}	4.81^{ns}	4.24^{ns}	11.99^{**}	20.20^{**}	6.34^{ns}	1.91^{ns}	-14.00^{**}	-6.50^{ns}	-11.50^{**}	3.97^{ns}	-1.60^{ns}	-6.20^{ns}	3.80^{ns}
	E3	-13.40^{**}	6.63^{ns}	11.10^{**}	0.00^{ns}	-4.28^{ns}	15.80^{**}	19.03^{**}	-9.10^{**}	-12.00^{**}	-17.00^{**}	-6.53^{ns}	0.74^{ns}	6.85^{ns}	-6.60^{ns}	22.50^{**}
DAT	E1	-2.98^{**}	-0.10^{ns}	0.98^{ns}	1.36^{*}	0.73^{ns}	-1.70^{**}	3.53^{**}	0.57^{ns}	0.61^{ns}	-0.60^{ns}	0.78^{ns}	1.65^{**}	1.80^{**}	-2.10^{**}	-0.90^{ns}
	E2	-0.85^{ns}	2.03^{**}	0.40^{ns}	0.65^{ns}	-2.23^{**}	-1.70^{**}	-0.85^{ns}	-0.93^{*}	4.36^{**}	-0.50^{ns}	3.28^{**}	-3.10^{**}	1.52^{**}	2.44^{**}	-1.50^{**}
	E3	-1.30^{**}	3.66^{**}	-5.60^{**}	0.08^{ns}	3.12^{**}	-3.80^{**}	-0.80^{*}	2.66^{**}	3.20^{**}	4.49^{**}	-0.88^{*}	-3.50^{**}	-1.40^{**}	0.45^{ns}	-3.40^{**}
DAS	E1	-2.93^{**}	1.11^{ns}	0.73^{ns}	0.36^{ns}	0.73^{ns}	-2.20^{**}	2.90^{**}	2.53^{**}	-0.30^{ns}	-1.10^{ns}	0.23^{ns}	1.94^{**}	1.64^{**}	-0.90^{ns}	-1.48^{*}
	E2	-0.54^{ns}	2.08^{**}	0.63^{ns}	1.08^{*}	-3.25^{**}	-1.70^{**}	-0.67^{ns}	-0.90^{ns}	3.79^{**}	-0.50^{ns}	1.92^{**}	-1.80^{**}	1.38^{**}	1.96^{**}	-0.80^{ns}
	E3	-1.61^{**}	2.60^{**}	-3.60^{**}	0.98^{*}	1.60^{**}	-3.50^{**}	-1.19^{**}	3.68^{**}	2.64^{**}	3.85^{**}	-1.28^{**}	-1.70^{**}	-0.10^{ns}	0.85^{*}	-3.40^{**}
ASI	E1	0.04^{ns}	1.21^{**}	-0.30^{ns}	-1.00^{**}	-0.00^{ns}	-0.50^{**}	-0.63^{**}	1.96^{**}	-0.90^{**}	-0.50^{**}	-0.54^{**}	0.29^{*}	-0.20^{ns}	1.17^{**}	-0.60^{**}
	E2	0.31^{ns}	0.06^{ns}	0.23^{ns}	0.43^{**}	-1.03^{**}	0.02^{ns}	0.18^{ns}	0.06^{ns}	-0.60^{**}	-0.10^{ns}	-1.4^{**}	1.35^{**}	-0.10^{ns}	-0.50^{**}	0.73^{**}
	E3	-0.31^{ns}	-1.10^{**}	1.98^{**}	0.90^{**}	-1.52^{**}	0.23^{ns}	-0.39^{*}	1.03^{**}	-0.60^{**}	-0.60^{**}	-0.39^{*}	1.86^{**}	1.35^{**}	0.40^{*}	-0.20^{ns}
KW	E1	38.03^{*}	52.20^{**}	111.00^{**}	-18.10^{ns}	-182.00^{**}	-19.00^{ns}	-104.4^{**}	2.81^{ns}	82.20^{**}	21.80^{ns}	-43.80^{**}	-120^{ns}	39.45^{*}	12.40^{ns}	98.50^{**}
	E2	3.02^{ns}	12.20^{ns}	-11.00^{ns}	-1.70^{ns}	-2.780^{ns}	42.20^{ns}	39.20^{ns}	50.52^{*}	-135.00^{**}	13.8^{ns}	-61.60^{**}	-6.60^{ns}	86.90^{**}	44.60^{ns}	99.70^{**}
	E3	45.81^{*}	-31.00^{ns}	55.9^{**}	-32.60^{ns}	-38.00^{ns}	146.00^{**}	-140.40^{**}	-7.30^{ns}	-44.00^{*}	66.00^{**}	-136.00^{**}	-44.60^{*}	-34^{ns}	-16.00^{ns}	142.00^{**}
GY	E1	0.49^{*}	0.62^{**}	0.46^{**}	-0.11^{ns}	-1.46^{**}	-0.3^{ns}	-0.41^{ns}	-0.44^{*}	0.64^{**}	0.02^{ns}	-0.01^{ns}	-0.40^{ns}	0.34^{ns}	0.27^{ns}	0.91^{**}
	E2	0.22^{ns}	-0.40^{ns}	0.07^{ns}	0.18^{ns}	-0.09^{ns}	0.24^{ns}	0.57^{**}	0.10^{ns}	-1.10^{**}	0.24^{ns}	-0.44^{ns}	0.33^{ns}	0.80^{**}	-0.10^{ns}	0.96^{**}
	E3	0.95^{**}	-0.50^{ns}	0.41^{ns}	-0.53^{*}	-0.36^{ns}	1.00^{**}	-0.44^{ns}	-0.20^{ns}	-1.30^{**}	0.03^{ns}	-0.95^{**}	0.40^{ns}	-0.2^{ns}	-0.20^{ns}	1.48^{**}

ns = non-significant, E1 = optimal irrigation, E2 = intermediate irrigation and E3 = low irrigation. LR: leaf rolling, LAI: leaf area index, PH: plant height, DAT: days to anthesis, DAS: days to silking and ASI: anthesis-silking interval, KW: 1000-kernel weight and GY: grain yield. P1: CML 161, P2: CML 424, P3: KSU 8–33, P4: KSU 4–58, P5: KSU 6–47, P6: 3–69.

* Significant at 5% probability level.

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showed significant negative SCA of days to anthesis and days to silking under E3 with values of (−0.88 and −1.28 respectively). P3 × P5 also revealed highly significant negative SCA of anthesis-silking interval under E1 and E2 (−0.54 and 1.4 respectively).

Furthermore, P3 × P6 depicted highly significant negative SCA of days to silking under E2 and E3 (−1.8 and −1.7 respectively). Highly significant negative SCA of leaf rolling was also recorded for this cross under E2 and E3 (−0.7 and −0.5 respectively). In addition, P3 × P6 gave SCA of days to anthesis under E2 and E3 (−3.1 and −3.5 respectively). For P4 × P5 highly significant negative SCA of days to anthesis was recorded under E3 (−1.4). The cross also displayed highly significant positive SCA of 1000-kernel weight (86.9), grain yield (0.80) under E2, and significant positive SCA of 1000-kernel weight under E1. P4 × P6 displayed highly significant negative SCA under E2 only (−0.50). Additionally, highly significant positive SCA of plant height (22.5) was recorded for P5 × P6 under E3, and highly significant positive SCA of 1000-kernel weight and grain yield under the three environments. The cross further showed highly significant negative SCA of days to anthesis was displayed under E2 and E3 (−1.5 and −3.4 respectively), with significant negative SCA of days to silking (−1.48) under E1. Highly significant negative SCA (−3.4) was also observed in this cross under E3 whereas highly significant negative SCA of anthesis-silking interval (−0.6) was found under E1.

4. Discussion

Highly significant environment variance observed in all characters indicated that the traits such as plant height (Mickelson et al., 2001), grain yield (Doerksen et al., 2003) and days to silking (Zare et al., 2011) were highly influenced by environmental factors. Highly significant GCA × environment and SCA × environment (P < 0.05) for almost all the traits showed that performance of inbred lines and F_1 hybrids was altered by rate of water applied, and thus testing inbred lines under different environments will ensure selection of stable parents that can perform to the potential of that environment (Machado et al., 2009) or emphasizing the importance of environment in phenotypic expression of agronomic characters (Bello and Olaoye, 2009). Testing inbreds under various environments is therefore important to ensure stable donor or tester for hybridization. In another reports Desai and Singh (2000), Nass et al. (2000) and Aguiar et al. (2003) obtained highly significant effects of environments, GCA, SCA, and their interaction with environment.

Highly significant GCA and SCA variances observed for almost all traits showed that hybrids and inbreds were different from each other for the traits under study and that variability in the breeding materials was attributable to additive and non-additive gene effects. Similar conclusion was made by Chaudhary et al. (2000), Nigussie and Zelleke (2001), El-Shouny et al. (2003), Aguiar et al. (2003) and Abdel-Moneam et al. (2009). The closer the ratio of GCA:SCA is to unity, the greater the predictability of progeny performance based on the GCA alone and the better the transmission of trait to the progenies. Less than one ratio of GCA:SCA observed in all environments for all characters revealed that these traits were purely under dominance effect of gene and that selection for these characters should be performed using recurrent selection method. This observation was in agreement with reports of Machado et al. (2009) and Abdel-Moneam et al. (2009). Despite these reports, other researchers indicated predominance of additive genetic effects for kernels per row plant height (Vacaro et al., 2002) and grain yield (Ojo et al., 2007).

The observed increase in the values of leaf rolling and reproductive characters as well as decrease in the values of grain yield, leaf area index, plant height, and 1000 kernel weight in this experiment confirmed the belief that water can adversely affect maize growth and yield. Reduction in maize yield under intermediate and severe stresses was previously reported (Uribelarrea et al., 2002 and Campos et al., 2006). It is vivid from the result that anthesis-silking interval is the most highly affected trait of maize under stress a result earlier reported by Hall et al. (1981). Higher performance of diallel hybrids for almost all characters over the environments compared to inbreds might arise in one hand from inbreeding depression effect of selfing the inbreds across several generations. In the other hand, the hybrids benefited from recombination of the favorable alleles thus suggesting the role of heterosis in the hybrids. This result suggests possible selection at early stage of maize drought improvement program. The relatively significant high yield 4.33 t ha^{-1} observed in P3 × P6 coupled with relatively long anthesis-silking interval under E2 and E3 implied that this genotype was receiving pollen from nearby late flowering lines a situation which may not happen under mono-varietal maize cropping.

Success of hybridization relies on obtaining parents to achieve improved genotypic combination, which cannot be guaranteed from parental values. Estimates of the GCA effects of the six parents in this study revealed that none of the parents had good general combining ability for all traits across the environments. The GCA effect estimated under optimal irrigation suggested the importance of P2 and P1 as the best donors for leaf area index, plant height and 1000 kernel weight, while P5 was the best donor for grain yield under optimal and intermediate environments. In addition, P6 was the best donor for early days to tasselling under the three environments. The SCA was the highest for grain yield and 1000-kernel weight under all the three environments in P5 × P6, whereas P1 × P2 was a good combination for grain yield under optimal and low environments. Furthermore, P1 × P3 and P2 × P6 were the best combination for leaf area index under optimal and low irrigations. The negative SCA for grain yield displayed by P1 × P6 hybrid indicated unsuitability of both parents as specific combiners for the trait. This finding was in line with that of Pswarayi and Vivek (2008) who also observed differences in the expression of GCA and SCA with stress.

Crosses involving at least one parent with high GCA effect would produce good segregates, if the additive genetic system present in one parent and complementary epistatic effects in the other act in the same direction to maximize the desirable plant attribute (Singh and Chaudhary, 1995). Looking at relation between parental line and cross performance for yield across all environments, we found that all hybrids with a good level of specific combining abilities P1 × P2, P1 × P3, P1 × P4 and P2 × P6 are products of parents with weak or negative GCA for yield under E1. The exceptions are hybrids with high SCA coming from low × high GCA parents. Under E2 all hybrids with significant SCA originated from source of which at least a parent has significant GCA, except P2 × P4 that originated from low × low GCA parents. Under E3 both P1 × P2 and P2 × P3 that had significant SCA for yield came from crossing low × high GCA parents; however, P5 × P6 came from low × low GCA parents. It can be concluded that weak relation was displayed between yield of the best parent and F_1 under E1 and E2, while medium relation was encountered under E3. This observation suggested the role of non-additive gene actions in the inheritance of tolerance to all environments, suggesting a need to advance to high generation before selection is made among the hybrids.

5. Conclusion

Maize inbred lines meant for stress tolerance program should be tested under stress environment before their inclusion into breeding program. The hybrids with superior SCA showed that dominance effect of gene is more active than additive action in inheritance of maize characters under low water condition. In this case, simple recurrent selection that focuses on SCA inbreeding should be employed for rapid and useful result during maize improvement. The current materials (inbreds and hybrids) can serve as good materials for further inbreeding and selection and additional evaluation in crosses.

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